Prestress Technology

*Product Research and Development*

# Exploration for New Technology of Assembled Corrugated Steel Web Composited Beam

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**Abstract:** Improving the prefabrication and assembly level of composited beams with corrugated steel web is key to promoting their application in bridge engineering for medium-span bridges. This paper first derives the principle of 'vertical composite force invariance' unique to composite beams with corrugated steel webs, and validates this principle using finite element structural models. Based on this, four new types of prefabricated and assembled continuous composite beams with corrugated steel webs are developed, and their respective characteristics are analyzed to provide references for other engineering practices.

**Keywords:** assembled; corrugated steel web composited beam; vertical assembly invariance of composite beam load-bearing state

**Citation:** Guo, X.; Zhang, S.; Zhao, C. Exploration for New Technology of Assembled Corrugated Steel Web Composited Beam. *Prestress Technology* **2024**, *4*, 69-82. https://doi.org/10.59238/j.pt.2024.04.005

Received: 04/09/2024
Accepted: 07/12/2024
Published: 30/12/2024

## 1 Introduction

Composite beams with corrugated steel webs are increasingly valued by the engineering community and researchers due to their advantages such as light weight, high shear strength of the web, and high prestressing efficiency [1-5]. Compared to cast-in-place construction, prefabricated composite beams with corrugated steel webs not only inherit all the advantages of corrugated steel webs but also possess the advantages of prefabricated structures. Specifically, prefabricated composite beams with corrugated steel webs have the following significant advantages:

(1) Effective solution to web cracking: The high shear strength and prestressing efficiency of the corrugated steel web significantly reduce the risk of web cracking.
(2) Fast erection: Prefabricated components can be produced in advance in the factory, and on-site installation is quick, greatly shortening the construction period.
(3) Quality control: Factory production can better control the quality of components, ensuring the precision and reliability of each step.
(4) Environmentally friendly: Prefabricated construction reduces on-site work, lowering construction noise and dust pollution, making it more environmentally friendly.

Despite the numerous advantages of prefabricated composite beams with corrugated steel webs, most bridges with spans of 30 to 60 meters currently use cast-in-place structures, resulting in a low degree of prefabrication and assembly. This severely limits the promotion and application of composite beams with corrugated steel webs in bridge construction [2]. To improve the prefabrication and assembly level of composite beams with corrugated steel webs, researchers and designers have conducted extensive studies and explorations. Reference [2] proposed the use of prefabricated I-shaped corrugated steel web composite beam units, forming a box section with external prestressed steel strands, and constructed the Zhangzhuang Village Separation Overpass with a span arrangement of 2 × 40 meters. Building on Reference [2], Reference [6-8] introduced a prefabricated corrugated steel web box girder structure using internal prestressing based on secondary prestressing technology, and constructed the Jialu River Bridge with a span arrangement of 2 × 50 m. References [9,10] proposed a segmental prefabrication and assembly scheme for narrow-width corrugated steel web composite box girders and conducted relevant experimental studies.

Table 1 summarizes the prefabricated composite beams with corrugated steel webs that have been built in China to date.

**Table 1** Some typical prefabricated composite beams with corrugated steel webs in China

| Project name | Span layout (m) | Bridge width(m) | Type of girder | Completion time |
|---|---|---|---|---|
| Xinyang Po River Bridge | 4×30 | 16 | Box beam | 2003 |
| Zhangzhuang Village Separation Overpass | 2×40 | 7 | Work first and then box beam | 2014 |
| Jialu River Bridge | 2×50 | 2×16.75 | Work first and then box beam | 2017 |
| Feiyun River Bridge on the Wencheng-Taishun Expressway | 10×40+30 | 2×12.25 | I-shaped cross-section beam | 2020 |
| The approach bridge of Yellow River Bridge in Mengzhou | 20×50 | 2×16.06 | Box beam | 2021 |
| The approach bridge of Yellow River Bridge in Fanxian Country | 13×47+40×50+(35+50+35) | 2×16.31 | Box beam | 2024 |
| The approach bridge of the Yellow River Bridge in Baiyan Township, Puyang | 113×50+2×(50+2×51+50) | 2×16.31 | Box beam | 2024 |
| The approach bridge of the Anluo Expressway Yellow River Bridge | 19×30+5×28 | 2×20.31 | I-shaped cross-section beam | Under construction |

The key to improving the industrialized construction level of prefabricated composite box girders with corrugated steel webs lies in adopting standardized and lightweight components while considering the amount and difficulty of on-site work to facilitate installation and connection. Therefore, prefabricated modular structures need to balance the relationship between component size, weight, and the number of joints. Existing research has provided many useful ideas for enhancing the prefabrication and assembly of composite box girders with corrugated steel webs, but there are also limitations: Prefabricated units and structural forms are single, unable to adapt to complex and varied construction conditions. Prestressing methods are single, failing to fully utilize the structural characteristics of corrugated steel webs.

Given these limitations, this paper first derives the principle of "vertical assembly invariance of composite beam load-bearing state" unique to composite beams with corrugated steel webs. Based on this principle, several prefabricated modular composite beam structures with corrugated steel webs are proposed, and the characteristics of various structures and construction methods are compared and analyzed to provide references for related engineering practices and research.

## 2 Technical Principles

### 2.1 *Basic Assumptions*

When subjected to longitudinal axial forces, corrugated steel plates undergo significant axial deformation. This means that the actual elastic modulus $E_x$ of the corrugated steel plate in the longitudinal direction is much lower than the initial elastic modulus $E_s$ of the steel material. This phenomenon is known as the "wrinkling effect" of the corrugated steel web. The actual elastic modulus $E_x$ of the corrugated steel web in the axial direction is referred to as the effective elastic modulus [11]. Consider a single wavelength of the corrugated steel plate under the action of an axial force $N$, as shown in Figure 1.

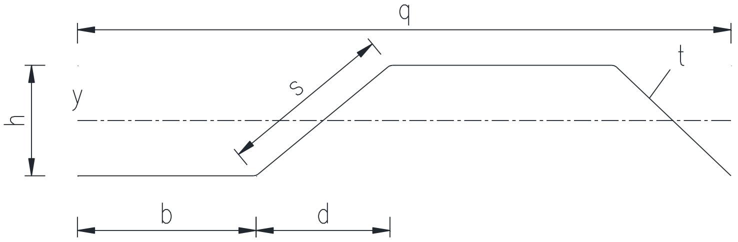


**Figure 1** Design parameter of corrugated steel plate

$$\delta_1 = \frac{N}{6E_sI}(\frac{s^3}{2} + 3h^2b) \tag{1}$$

For an equal-length flat steel plate, the deformation under the action of an axial force $N$ is given by:

$$\delta_2 = \frac{2N(b+d)}{E_sA} \tag{2}$$

According to Castigliano's theorem, setting $\delta_1 = \delta_2$ yields:

$$E_x = E_s \cdot \frac{(b+d)}{a^3/(2h)^2 + 3b} \cdot \frac{t^2}{h^2} \tag{3}$$

For a 1600-type corrugated steel web [11], the design parameters $b$, $d$, $\hbar$, and $t$ are taken as 430 mm, 370 mm, 220 mm, and 12 mm, respectively. Substituting these values into Equation (3) yields $E_x = E_s/723$. This shows that the axial effective elastic modulus of the corrugated steel web is much smaller compared to the elastic modulus of the steel itself. The characteristic of the corrugated steel plate having weak longitudinal axial force and bending moment resistance is called the wrinkling effect.

Based on the wrinkling effect of the corrugated steel plate, the following basic assumptions are made for composite box girders with corrugated steel webs [11]:

(1) The entire vertical shear force is borne by the corrugated steel web.

(2) The bending moment is carried solely by the upper and lower concrete slabs, and the plane strain conforms to the assumption of a nearly flat section.

### 2.2 *Principle of Vertical Load-Bearing Invariance*

#### 2.2.1 Formula Derivation

To verify the "vertical assembly invariance of composite beam load-bearing state" of composite beams with corrugated steel webs, we compare a composite beam consisting of a concrete slab and an I-shaped corrugated steel web. Figure 2 shows a prefabricated concrete slab with prestressed steel strands inside, assuming the total prestress force is $N$. The stress $\sigma_C$ in the cross-section of the concrete slab can be expressed by Equation (4):

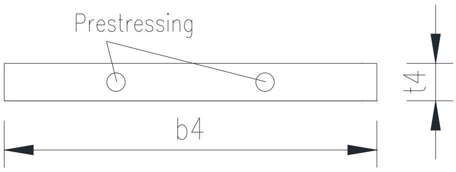


**Figure 2** Prefabricated concrete slab with prestressed steel strands inside

$$\sigma_C = -N/b_4t_4 \tag{4}$$

where

$\sigma_C$ is the stress in the concrete slab,

$N$ is the total prestress force,

$b_4t_4$ is the cross-sectional area of the concrete slab.

Based on Figure 2, add a concrete top slab and a corrugated steel web to form an I-shaped composite beam with a corrugated steel web, as shown in Figure 3. Similarly, a total prestress load $N$ is applied to the bottom slab.

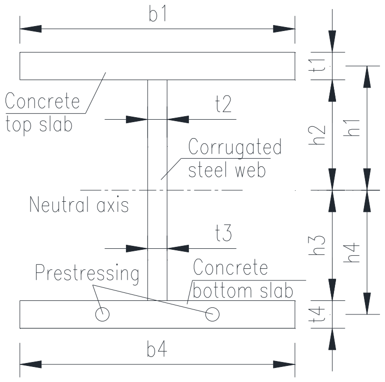


**Figure 3** I-shaped composite beam with a corrugated steel web

Since the cross-section is an I-shaped section and the prestressing tendons are in located in the concrete bottom slab, the prestress will generate a negative moment $M$ in the composite cross-section, as shown in Equation (5):

$$M = N/(t_4/2 + h_3) \tag{5}$$

By equating the static moments of the sections above and below the neutral axis, obtain Equation (6). The total cross-sectional area $A$ and the moment of inertia $I$ of the composite beam are given by Equations (7) and (8).

$$b_1t_1h_1 + h_2t_2\frac{h_2}{2} = h_3t_3\frac{h_3}{2} + b_4t_4h_4 \tag{6}$$

$$A = b_1t_1 + h_2t_2 + h_3t_3 + b_4t_4 \tag{7}$$

$$I = \frac{b_1t_1^3}{12} + b_1t_1h_1^2 + \frac{t_2h_2^3}{12} + t_2h_2\left(\frac{h_2}{2}\right)^2 + \frac{t_3h_3^3}{12} + t_3h_3\left(\frac{h_3}{2}\right)^2 + \frac{b_4t_4^3}{12} + b_4t_4h_4^2 \tag{8}$$

Based on the wrinkling effect of the corrugated steel plate, we can assume $t_2 = t_3 = 0,\ t_1 = t_4 = t,\ h_4 = h_3 + t/2,\ h_1 = h_2 + t/2$. Therefore, Equations (5) to (8) can be simplified to Equations (9) to (12).

$$M = Nh_4 \tag{9}$$

$$b_1h_1 = b_4h_4 \tag{10}$$

$$A = t(b_1 + b_4) \tag{11}$$

$$I=\frac{(b_1+b_4)t^3}{12}+t(b_1h_1^2+b_4h_4^2)=\frac{At^2}{12}+\frac{b_1h_1^2}{b_4}A \tag{12}$$

Based on the axial compressive force $N$ and the bending moment $M$ acting on the main beam, the stresses $\sigma_T$ and $\sigma_B$ in the top and bottom slabs can be determined.

$$\sigma_T=-\frac{N}{A}\left(1-\frac{12h_1h_4}{t^2+12h_1h_4}\right)=-\frac{N}{A}\frac{1}{1+12\frac{h_1h_4}{t^2}} \tag{13}$$

$$\sigma_B=-\frac{N}{A}\left(1+\frac{12(\frac{h_4}{t})^2}{1+12\frac{h_1h_4}{t^2}}\right) \tag{14}$$

For conventional composite beam cross-sections, the thickness $t$ of the top and bottom slabs is typically much smaller compared to $h_1$ and $h_4$. Therefore, the stresses $\sigma_T$ and $\sigma_B$ can be simplified as follows:

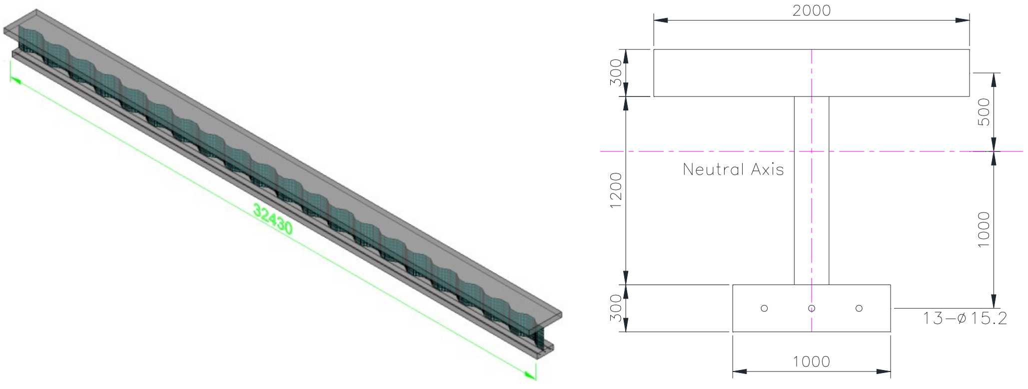
$$\sigma_T\approx 0 \tag{15}$$

$$\sigma_B=-\frac{N}{b_4t}\cdot\frac{h_1}{h_1+h_4}\cdot\left(\frac{t^2+12h_1h_4+12h_4^2}{t^2+12h_1h_4}\right)\approx -N/b_4t \tag{16}$$

By comparing Equation (4) and Equation (16), it can be observed that when the height of the composite beam is relatively large, the stress state of a single concrete slab is essentially the same as the stress state of the concrete bottom slab in a composite beam with a corrugated steel web. This means that the prestress initially applied to the prefabricated bottom slab will not be transferred to the top slab or the corrugated steel web after the composite beam is assembled; its magnitude remains essentially unchanged. In this paper, the property where the load-bearing state of a composite beam with a corrugated steel web remains essentially unchanged before and after vertical assembly is referred to as the "vertical assembly invariance of composite beam load-bearing state" of composite beams with corrugated steel webs.

### 2.2.2 Finite Element Method Verification

A simply supported composite beam with a corrugated steel web has a span of 32.430 meters, and the cross-section is shown in Figure 4. The top and bottom slabs of the composite beam are made of C50 concrete, and the corrugated steel web is of the 1600-type with a thickness of 12 mm, made of Q345qD steel. The bottom of the beam is equipped with three bundles of 13-$\phi^s$15.2 prestressing tendons, with a tension control stress of 1,395 MPa. After accounting for prestress losses, the average effective stress is 1,260 MPa.



a) 3D model b) Cross-section form

**Figure 4** Composite beam with Corrugated steel web model (Unit: mm)

The finite element model of the structure was established using ABAQUS 2016. The concrete slabs were modeled using C3D8R solid elements, the corrugated steel web using S4R shell elements, and the prestressing tendons using T3D3 truss elements. Both the corrugated steel web and the prestressing tendons are connected to the concrete using the "embedded" method. The model only considers the prestress load and does not include the self-weight of the structure or other external loads. The finite element model of the composite beam is shown in Figure 5.

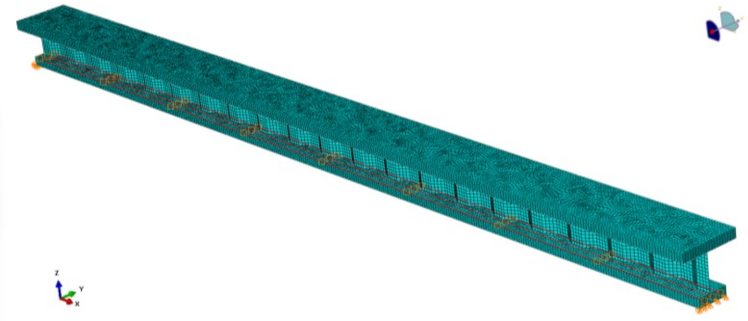
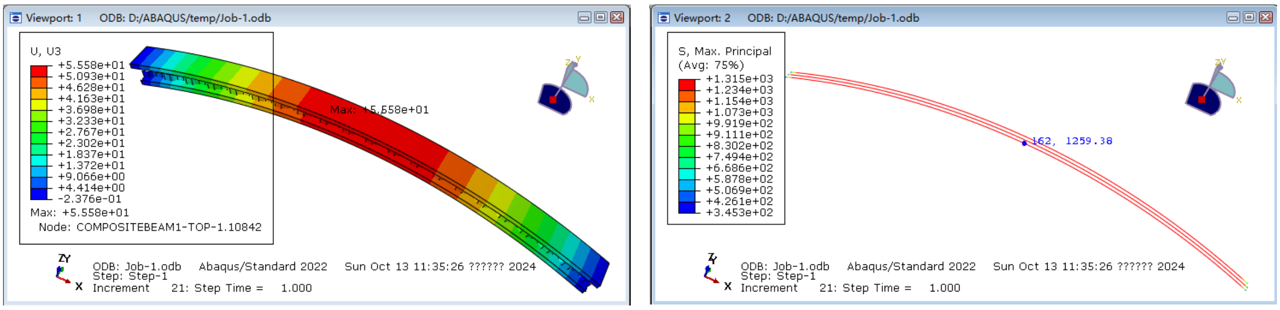


**Figure 5** Finite element model of composite beam corrugated steel web

For a simply supported composite beam with a corrugated steel web, under the action of prestress load, the mid-span deflection $w$ is given by Equation (17). Where $l$ is length of beam, $E_c$ is the elastic modulus of the concrete slab, $M$ and $I$ is the moment and moment of inertia, respectively. The deflection formula does not consider the flexural stiffness of the corrugated steel web. Since the self-weight is not considered, the deflection direction is upward.

$$w = Ml^2/8E_cI \tag{17}$$

The finite element calculation results are shown in Figure 6. After organizing the finite element results, they are compared with the theoretical results from Equations (13), (14), and (17), as presented in Table 2. It can be observed that the average stress in the bottom slab and the maximum deflection have very small deviations, both within 5%. The deviation in the top slab stress is relatively larger, but considering that the stress value in the top slab is small, the actual deviation is also not significant.



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Step: Step-1
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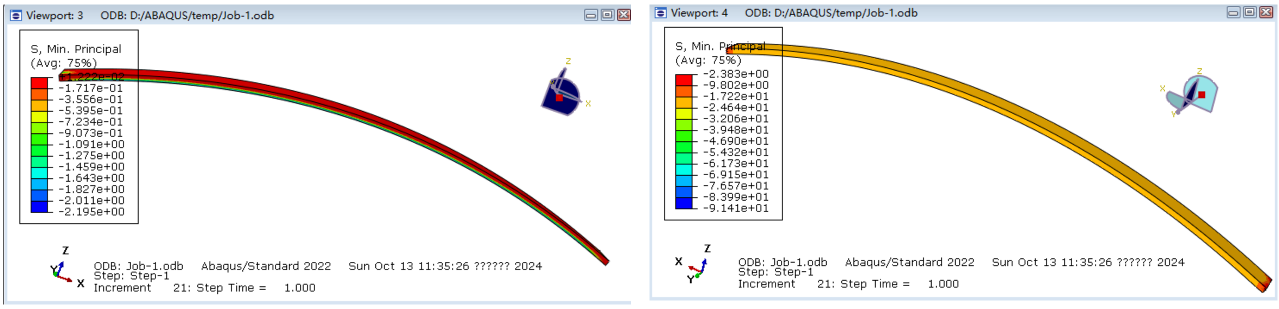
a) Composite beam displacement (mm) b) Maximum principal stress in prestressing tendons (MPa)



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ODB: Job-1.odb    Abaqus/Standard 2022    Sun Oct 13 11:35:26 ?????? 2024
Step: Step-1
Increment     21: Step Time =    1.000
```

c) Minimum principal stress in top slab (MPa) d) Minimum principal stress in bottom slab (MPa)

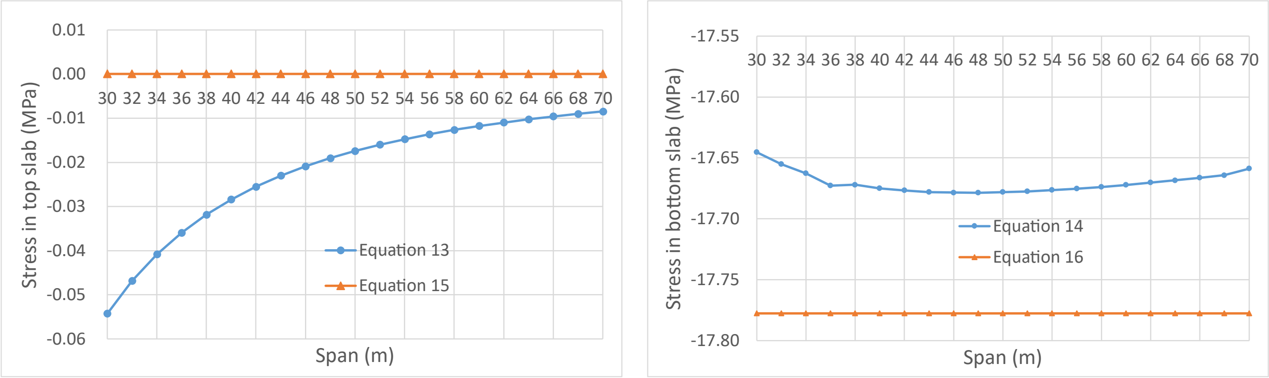
**Figure 6** Finite Element Calculation Results

**Table 2** Comparison of finite element results and theoretical results

| Parameter | Finite element result | Theoretical result | Deviation value |
|---|---|---|---|
| Stress in top slab (MPa) | -0.58 | -0.11 | -0.47 |
| Stress in bottom slab (MPa) | -21.96 | -22.7 | 0.74 |
| Maximum deflection (mm) | 55.58 | 57.39 | -1.81 |

### 2.3 *Comparison of Applicability for Different Span Lengths*

According to reference [8], the suitable span length for composite beams with corrugated steel webs is between 30 to 60 meters. When the span exceeds 80 meters, the beam height will surpass 5 meters, leading to structural instability before strength failure, making it unsuitable for such spans. Generally, the reasonable ratio of beam height to span for composite beams is between 1/16 to 1/18, and the bridge deck width has little impact on the beam height. Assuming a composite beam with a top slab width of 8 meters, a bottom slab width of 4.5 meters, a height-to-span ratio of 1/16, a top and bottom slab thickness of 0.25 meters, a 1600-type corrugated steel web, and a steel plate thickness of 12 millimeters, the effective prestress load on the bottom slab is 2.0E+07 N. The theoretical results of the main compressive stresses in the top and bottom slabs of the main beam, before and after simplification, are illustrated in Figure 7. The cross-sectional area and moment of inertia before simplification were calculated using formulas (7) to (8), while those after simplification were determined using formulas (11) to (12).



a) Stress in top slab of composite beam b) Stress in bottom slab of composite beam

**Figure 7** Comparison of theoretical results of main compressive stresses in the top and bottom slabs of the main beam before and after simplification

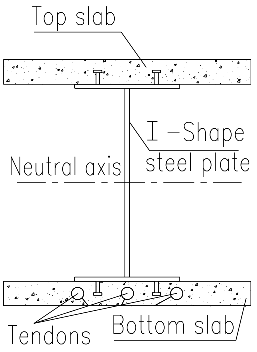
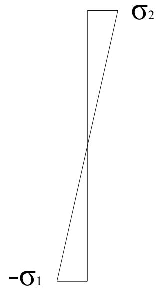
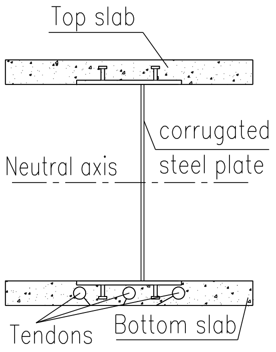
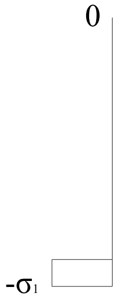
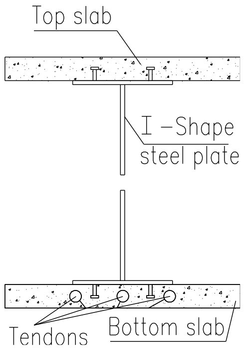
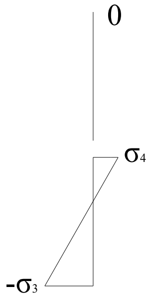
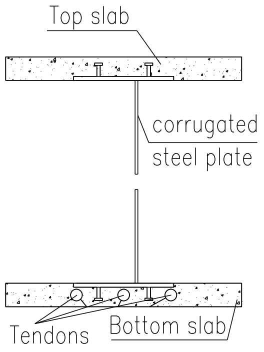
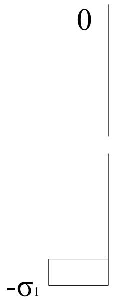
From Figure 7, it can be seen that when the span is smaller, due to the lower height of the composite beam, the "corrugation effect" of the corrugated steel web is weaker, thus the error between the results obtained using the simplified calculation formula and the actual values gradually increases; however, overall, the error in using the simplified formula meets the engineering precision requirements. This also corroborates the principle of "vertical assembly invariance of composite beam load-bearing state" of the composite beam structure with corrugated steel webs.

## 3 Vertical Splitting and Superposition Process Stress Comparison

Building upon the previous analysis, this section compares the stress changes in the top and bottom plates during the vertical installation and disassembly processes for I-girders with straight webs and corrugated steel webs. Here, prestress is considered as the only external force, with the sign convention being negative for compression and positive for tension.

### 3.1 *Stress Analysis During the Vertical Splitting Process*

**Table 3** Stress Analysis During the Vertical Splitting Process

| **Item** | **Straight web composite beam** | | **Corrugated steel web composite beam** | |
|---|---|---|---|---|
| | **Cross-section** | **Normal stress distribution** | **Cross-section** | **Normal stress distribution** |
| State 1: I-shaped composite beam |  |  |  |  |
| State 2: vertical splitting |  |  |  |  |

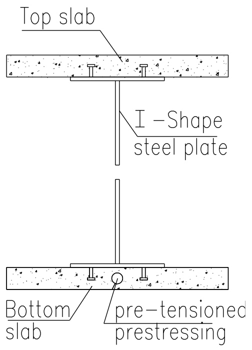
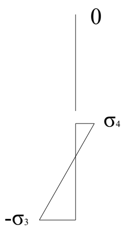
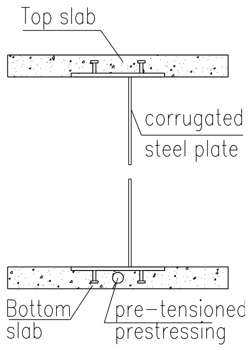
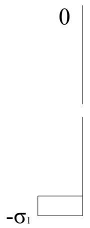
From the analysis in Table 3, it can be concluded that:

(1) For the straight web composite I-beam, after vertical splitting, a new centroidal axis is formed, and the prestress effect in the bottom slab will transfer among the top slab, bottom slab, and web.

(2) For the corrugated steel web composite beam, after vertical splitting, the prestress in the bottom slab will not transfer to other components.

### 3.2 *Stress Analysis During the Vertical Assembling Process*

**Table 4** Stress analysis during the vertical assembling process

| **Item** | **Straight web composite beam** | | **Corrugated steel web composite beam** | |
|---|---|---|---|---|
| | **Cross-section** | **Normal stress distribution** | **Cross-section** | **Normal stress distribution** |
| State 1: T-shaped composite beam |  |  |  |  |

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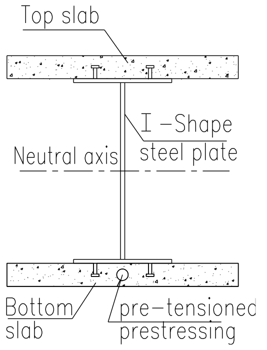
<td>
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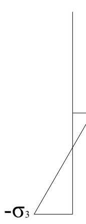
<td>
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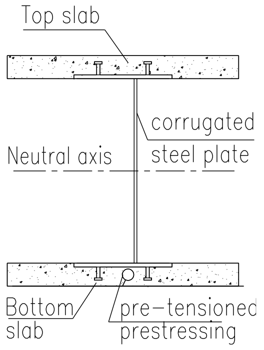
<td>
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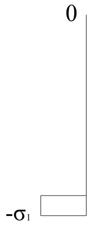
<td>
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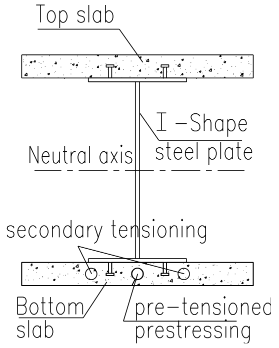
<td>
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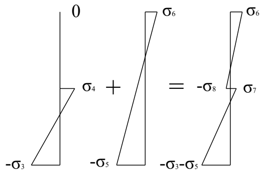
<td>
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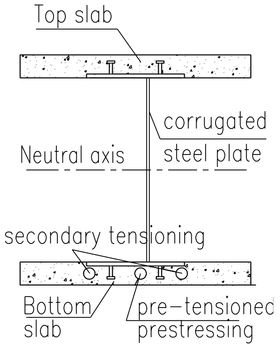
<td>
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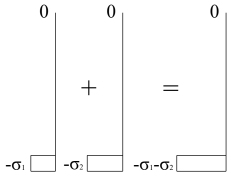
<td>
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</table>

From the analysis in Table 4, it can be concluded that:

(1) For the straight web composite beam, the centroidal axis of the section changes before and after vertical assembling, and the secondary prestress applied to the bottom plate will be redistributed across the entire section according to the assumption of a flat section.

(2) For the corrugated steel web composite beam, the centroidal axis of the section also changes, but the prestress applied at different times (pre-tensioning and secondary tensioning) do not interfere with each other and will not be transferred across the section.

## 4 New Structural Development and Conceptual Design

Based on the unique principle of vertical assembly invariance of composite beams with corrugated steel webs load-bearing state, and considering the transportation and erection of prefabricated components, a strategy of "dividing the whole into parts" and then "reintegrating the parts" has been adopted. Four new types of prefabricated composite beams with corrugated steel webs have been proposed, and a conceptual design is presented for bridges with a width 16.5 meters and spans ranging from 30 to 60 meters. "Primary tendons" refer to the tendons tensioned in the prefabrication factory, while "secondary tendons" refer to the tendons tensioned at the construction site.

### *4.1 Four Types of New Prefabricated Composite Beams with Corrugated Steel Webs and Their Characteristics*

#### 4.1.1 New Prefabricated Composite Beam with Corrugated Steel Web—System I

Two I-beam units are prefabricated in the factory and primary tendons are tensioned. After the I-beam units are hoisted into place, they are connected to form a box section using transverse wet joints. Secondary tendons are then tensioned in the prefabricated bottom slab and the secondary negative moment tendons at the pier top. The characteristics of this system are:

(1) The prefabricated main beam units are lightweight and easy to transport.
(2) There are multiple plate components and numerous wet joints.
(3) Tendons are tensioned in multiple batches.

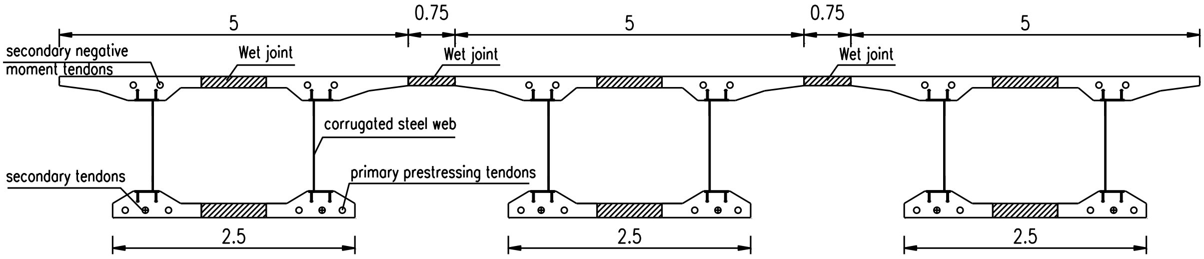

**Figure 8** Schematic diagram of composite beam structure section - system I (Unit: m)

### 4.1.2 New Prefabricated Composite Beam with Corrugated Steel Web—System II

In the factory, the top slab with flanges, the bottom slab, and the corrugated steel web are prefabricated separately. The bottom slab adopts primary prestressing tendons. After the top slab, bottom slab, and corrugated steel web are prefabricated, they are transported to the construction site for secondary assembly. At the site, the corrugated steel web is vertically connected using bolts to form a box section. The box unit is then hoisted into place and connected using transverse wet joints. Finally, the secondary negative moment tendons at the pier top are tensioned. The characteristics of this system are:

(1) The prefabricated units are lightweight and easy to transport.
(2) There are multiple slab components, requiring secondary assembly at the construction site.
(3) High connection precision is required.
(4) Fewer tendon tensioning batches are needed.

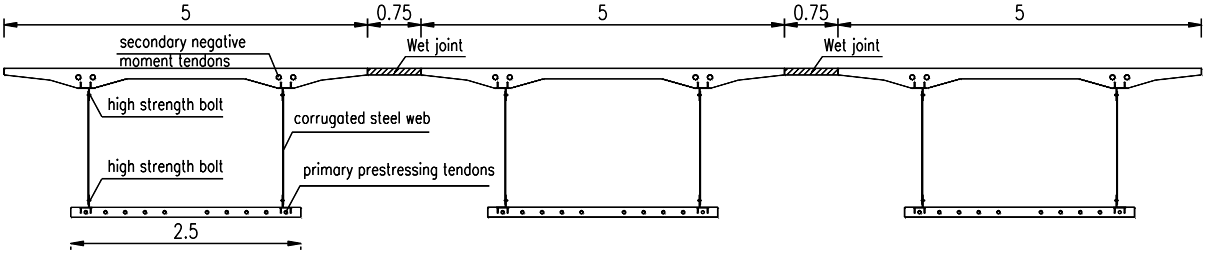

**Figure 9** Schematic diagram of composite beam structure section – system II (Unit: m)

### 4.1.3 New Prefabricated Composite Beam with Corrugated Steel Web—System III

In the factory, the top and bottom slabs with shear key slots and the corrugated steel web units are prefabricated. The bottom slab adopts primary prestressing tendons. After the prefabricated units are completed, they are transported to the construction site for secondary assembly. At the site, concrete is poured into the shear key slots to form a box section. The box unit is then transported to the final position and hoisted into place, and connected using transverse wet joints. Finally, the secondary negative moment tendons at the pier top are tensioned. The characteristics of this system are:

(1) The prefabricated units are lightweight and easy to transport.
(2) There are fewer slab components, reducing the number of on-site connections.
(3) Slightly higher connection precision is required at the construction site.
(4) Fewer tendon tensioning batches are needed.

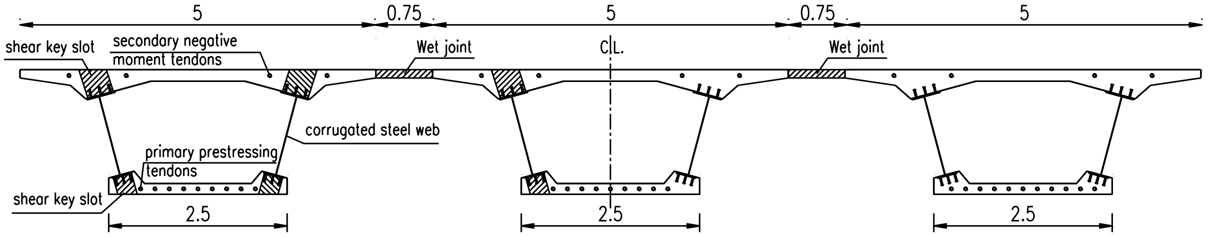

**Figure 10** Schematic diagram of composite beam structure section – system III (Unit: m)

### 4.1.4 New Prefabricated Composite Beam with Corrugated Steel Web—System IV

In the factory, U-shaped beams and waffle top slabs are prefabricated separately, with the bottom slab of the U-shaped beam adopts primary prestressing tendons. After the prefabricated units are completed, they are transported to the construction site. The U-shaped beams and waffle top slabs are then hoisted into place sequentially and connected using transverse wet joints. Finally, the secondary negative moment tendons at the pier top are tensioned. The characteristics of this system are:

(1) The prefabricated units are heavy, and the U-shaped beams are inconvenient to transport.
(2) There are fewer plate components, reducing the amount of on-site work.
(3) Moderate on-site work is required.
(4) More tendon tensioning batches are needed.

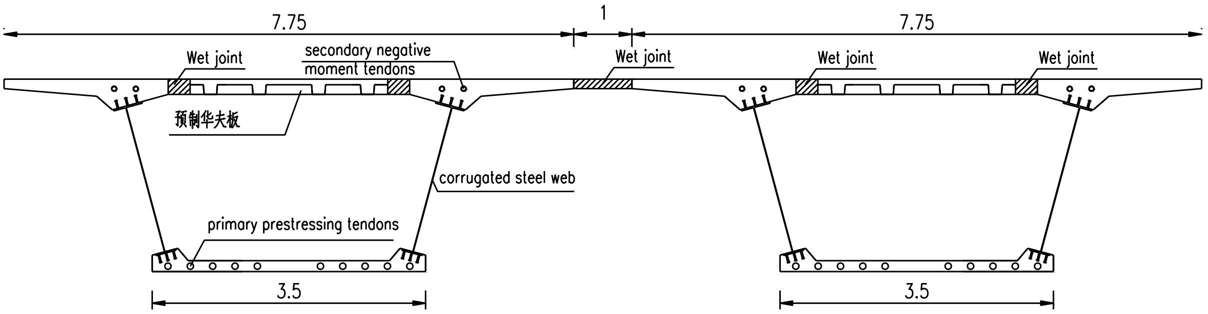

**Figure 11** Schematic diagram of composite beam structure section – system IV (Unit: m)

## *4.2 Comparison of Four Types of New Prefabricated Composite Beams with Corrugated Steel Webs*

All four types of new prefabricated composite beams with corrugated steel webs use internal prestressing tendons. They differ in terms of bottom slab prestress, structural integrity, and construction convenience. The specific differences are as follows:

(1) Bottom Slab Prestress Form:

System I: The prefabricated bottom slab uses primary prestressing tendons to resist the self-weight and construction equipment loads during the girder erection stage. After forming the box section, secondary prestressing tendons are tensioned in the bottom slab to resist the loads during the bridge completion stage. System I is suitable for a wide range of spans.

Systems II to IV: The prefabricated bottom slab uses primary prestressing tendons, which are fully tensioned during the bottom slab prefabrication stage, greatly simplifying the on-site prestressing tendon tensioning process. This makes the construction procedures simpler and more economical. However, Systems II and III are more suitable for shorter spans, while System IV, with its partially prefabricated waffle top slab and wider box cells, is suitable for longer spans.

(2) Structural Integrity:

System I and IV: The horizontal direction has two wet joints, resulting in poorer structural integrity. The age difference between the wet joint concrete and the prefabricated concrete, along with the difficulty of ensuring on-site concrete quality, can lead to potential issues.

Systems II and III: These systems offer better structural integrity than Systems I and IV, but special attention must be paid to the construction quality of bolts and shear keys.

(3) Construction Convenience:

System I: Requires casting two wet joints in the top and bottom slabs, increasing the formwork workload and making construction less convenient. Additionally, temporary supports are needed during the main beam installation stage to prevent lateral tilting.

Systems II and III: Require secondary assembly in the factory, including bolt assembly and shear key concrete pouring, to ensure smooth connections between prefabricated components. High precision is required for both prefabrication and construction.

System IV: Only requires casting the top slab wet joint, making construction more convenient. However, the prefabricated U-shaped beams are irregular components, making transportation difficult and requiring high lifting capacities during erection.

**Table 5** Comparison of characteristics of four types of new prefabricated composite beams with corrugated steel webs

| **System No.** | **Block forms** | **Assembly method** | **Prestress forms** | | **Structure features** |
|---|---|---|---|---|---|
| | | | **Bottom slab** | **Top slab** | |
| System I | Two prefabricated I-beams | Horizontal wet joints | Primary prestressing tendons + secondary tendons | Post-tensioned negative moment tendons | Can apply prestress according to construction load requirements. |
| System II | Prefabricated top and bottom slabs with flanges; Prefabricated corrugated steel web | Vertical bolt assembly | Primary prestressing tendons | | Good Structural Integrity of top and bottom slabs;<br>Can eliminate corbel for the prefabricated bottom slab |
| System III | Prefabricated top and bottom slabs; Prefabricated I-beam with corrugated steel web | Horizontal wet joints | Primary prestressing tendons | | Connected using bundled shear studs; Can use inclined web plates, providing good torsional resistance and aesthetic appearance. |
| System IV | Prefabricated U-shaped beams; Prefabricated waffle slab | Horizontal wet joints | Primary prestressing tendons + secondary tendons | | Suitable for wider box sections; Uses waffle top slab for high section efficiency; Can use inclined webs, providing good torsional resistance and aesthetic appearance. |

Compared to conventional bridge schemes, composite beams with corrugated steel webs offer economic advantages [12]. Since the structural differences among the four types of new prefabricated composite beams with corrugated steel webs are minimal, their economic differences are not significant. The analysis of applicable spans, construction, and aesthetics is provided in Table 6.

**Table 6** Comparison of four types of new prefabricated composite beams with corrugated steel webs

| System No. | Applicable span (m) | Single beam lifting weight (t) | Construction features and difficulty | Aesthetic effect |
|---|---|---|---|---|
| System I | 30~60 | 120~240 | On-site casting of 8 wet joints, tensioning of secondary tendons and negative moment tendons; many procedures, large workload, low construction difficulty. | Middle |
| System II | 30 | 230 | Secondary assembly required, casting of 3 wet joints, tensioning of negative moment tendons; many procedures, large workload, high construction difficulty. | Poor |
| System III | 30 | 230 | Secondary assembly required, on-site casting of 3 wet joints, tensioning of negative moment tendons; slightly more procedures, slightly larger workload, slightly higher construction difficulty. | Good |
| System IV | 60 | 500 | On-site casting of 5 wet joints, tensioning of secondary tendons and negative moment tendons; slightly more procedures, moderate workload, low construction difficulty. | Best |

Through the comparison of the four types of new prefabricated composite beams with corrugated steel webs, it is evident that different structural systems are suitable for different bridge spans, construction equipment, and construction techniques. Each system has its own characteristics and can be selected based on the specific project requirements.

## 5 Conclusions

Improving the prefabrication and assembly level of composite beams with corrugated steel webs for spans of 30 to 60 meters is key for promoting their application in bridge construction. This paper first derived and proved the unique "vertical assembly invariance of composite beam load-bearing state" principle of composite beams with corrugated steel webs. Based on this, four new prefabricated composite beam systems with corrugated steel webs were proposed. The characteristics of each system were analyzed in terms of structural form, construction advantages and disadvantages, and applicable spans, aiming to provide references for related engineering practices and research.

**Conflict of interest**: All the authors disclosed no relevant relationships.

**Data availability statement**: The data that support the findings of this study are available from the corresponding author, Zhang, upon reasonable request.

**Funding:** This research was funded by Science and Technology Plan Project of Henan Provincial Department of Transportation, grant numbers are 2017T09 and 2018J10.

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